maximum around ~1,000 million years ago. (However, although a temporal variation is clearly confirmed, we also point out that the compositional bias in the heavy noble-gas abundances in the solar wind has not varied very much in the past several thousand millions years.)

Future experimental and theoretical work will be needed to clarify the causes of this variability. In high-speed solar wind emanating from polar coronal holes the FIP-effect is 2–3 times less pronounced than in the normal solar wind[25,26], a finding that has recently been extended to additional elements by use of the SWICS instrument on the Ulysses probe orbiting over the solar poles[3]. Thus, a higher relative contribution of high-speed solar wind in the ancient samples might explain their smaller Kr-Ar bias. However, the opposite temporal trends of Xe and Kr enhancement factors suggest that other processes are also involved. One explanation that has been discussed[27] is that the relative contribution of transient solar wind associated with coronal mass ejections has been higher in the past. Elemental abundances in this type of solar wind are very variable but not constrained well enough to rule on this proposal[28]. A further observational constraint is that the Kr and Xe enhancement factors are basically the same for the solar wind and the higher-energy solar energetic particle component, as shown by the etch experiments[6]. Our results reinforce the unique importance of the lunar regolith for solar physics; not only does it enable us to analyse solar species that are too rare to be detected *in situ* with present-day instruments, but it also conserves a record of the ancient Sun not otherwise available. □

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A compound refractive lens for focusing high-energy X-rays

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THE development of techniques for focusing X-rays has occupied physicists for more than a century. Refractive lenses, which are used extensively in visible-light optics, are generally considered inappropriate for focusing X-rays, because refraction effects are extremely small and absorption is strong. This has lead to the development of alternative approaches[1,2] based on bent crystals and X-ray mirrors, Fresnel and Bragg–Fresnel zone plates, and capillary optics (Kumakhov lenses). Here we describe a simple procedure for fabricating refractive lenses that are effective for focusing of X-rays in the energy range 5–40 keV. The problems associated with absorption are minimized by fabricating the lenses from low-atomic-weight materials. Refraction of X-rays by one such lens is still extremely small, but a compound lens (consisting of tens or hundreds of individual lenses arranged in a linear array) can readily focus X-rays in one or two dimensions. We have fabricated a compound lens by drilling 30 closely spaced holes (each having a radius of 0.3 mm) in an aluminium block, and we demonstrate its effectiveness by focusing a 14-keV X-ray beam to a spot size of 8 μm.

The index of refraction for X-rays in matter can be written as $n = 1 - \delta + i\beta$, where β is the absorption index and δ is the refractive index decrement. Refraction being very small (δ is typically between 10^{-5} and 10^{-7}), all attempts to date to build refractive lenses for X-rays have been unsuccessful. Recently, the discussion about refractive lenses has been revived. Suehiro, Miyaji and Hayashi[3] have proposed a refractive lens of high-atomic-number (high-Z) material for focusing X-rays. Michette[4]

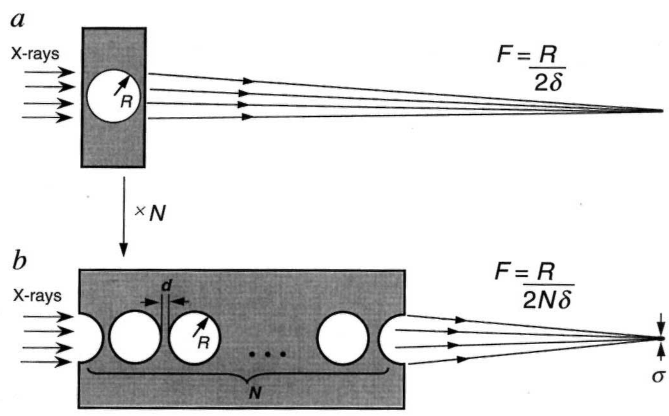

FIG. 1 Schematic diagram showing the principles of X-ray focusing by a compound refractive lens (CRL). As $(1 - \delta)$ is smaller than 1 (where δ is the decrement of the refractive index), a collecting lens for X-rays must have a concave shape. *a*, A simple concave lens fabricated as a cylindrical hole in the material. *b*, A CRL consisting of a number (N) of cylindrical holes placed close together in a row along the optical axis, focuses the X-rays at a distance that is N times shorter compared to a single lens. R is the radius of the holes, d is the spacing between the holes, λ is the X-ray wavelength, and F is the focal distance for a parallel input beam.

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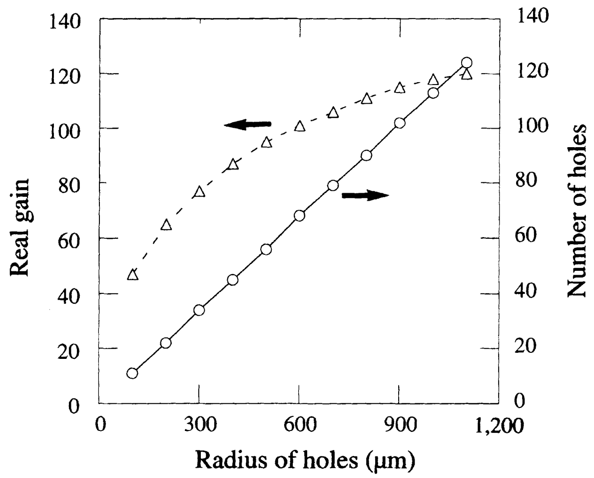

FIG. 2 Calculated number of holes N and real gain g versus radius of the holes R for a boron lens at fixed 1-m focal distance (10-keV X-rays). The number of holes increases linearly with increasing hole radius. Significant gain can be obtained with relatively few holes.

opposed the idea of using these lenses for soft X-rays because absorption dominates in that region. Yang[5] considered the possibility of making X-ray refractive lenses for hard X-rays using low-Z materials. However, the low values of δ for low-Z materials implies lens radii of only a few micrometres. To overcome this problem, we propose the construction of a compound refractive lens (CRL), consisting of a linear array of many simple lenses manufactured in low-Z material (such as boron, carbon, aluminium, polymers or water). Figure 1 shows such an arrangement that results in a line focus of X-rays. A single lens (Fig. 1a) has a focal distance $F = R/2\delta$ where R is the radius of the lens. A compound lens with N holes has a focal length $F = R/2N\delta$. For example, for aluminium at an X-ray energy of 14 keV, $\delta = 2.8 \times 10^{-6}$. Hence $F = 54$ m for an individual lens, whereas the compound lens with, say, 30 holes brings the focal length into a range acceptable for many microfocus experiments ($F = 1.8$ m).

We made a theoretical analysis of the CRL based on the Fresnel–Kirchhoff approach. Here we present the main results demonstrating the useful properties of this type of lens, omitting the derivation of formulas.

First, the CRL acts as a normal conventional lens and we can apply the Gauss lens formula, which relates the source distance r_0, the image distance r_f and the focal length F via $r_f = Fr_o/(r_0 - F)$. The diffraction-limited resolution of the lens σ_f is defined by an effective lens aperture A:

$$\sigma_f = \frac{\lambda r_f}{A} \tag{1}$$

where λ is the X-ray wavelength. For example, a lens of 500-μm aperture with 1-m focal distance should have a resolution of 0.2 μm.

To a first approximation, the aperture of the lens is $2R$. But if we neglect the absorption, only the central part of the cylindrical hole has the required parabolic shape of an ideal lens. Hence the aperture can be expressed as:

$$A_t = 2R\left(4\frac{\lambda r_f}{R^2}\right)^{\frac{1}{4}} \tag{2}$$

But when absorption suppresses the contribution of the outer parts of the lens, the aperture is given by:

$$A_a = 2R\left(\frac{2}{\mu R N}\right)^{\frac{1}{2}} \tag{3}$$

Here $\mu = 4\pi\beta/\lambda$ is a linear absorption coefficient. The real aperture of the CRL is the smaller of the two values given by equations (2) and (3).

An important feature of focusing optics is the intensity gain in the focal spot compared with the intensity which would have been obtained without a lens, using a collimated pinhole or slit. The ideal gain G, defined for a point source, is given by energy conservation as:

$$G = \frac{A}{\sigma_f}\left(1 + \frac{r_f}{r_0}\right) \tag{4}$$

When absorption defines the aperture, $G = 4\delta/\pi\beta$. The real gain g takes into account the source size σ_0 and X-ray absorption in the lens material:

$$g = aG\frac{\sigma_f}{\sigma_1} = a\frac{A}{\sigma_0}\left(\frac{r_0}{r_f} + 1\right) \tag{5}$$

where $a = \exp(-\mu N d)$ and $\sigma_1 = \sigma_0 r_f/r_0$ is the real focus size defined as a demagnified projection of the source size.

The real gain and the required number of holes are shown in Table 1 as a function of photon energy for boron and aluminium compound lenses. Figure 2 gives the number of holes in the array

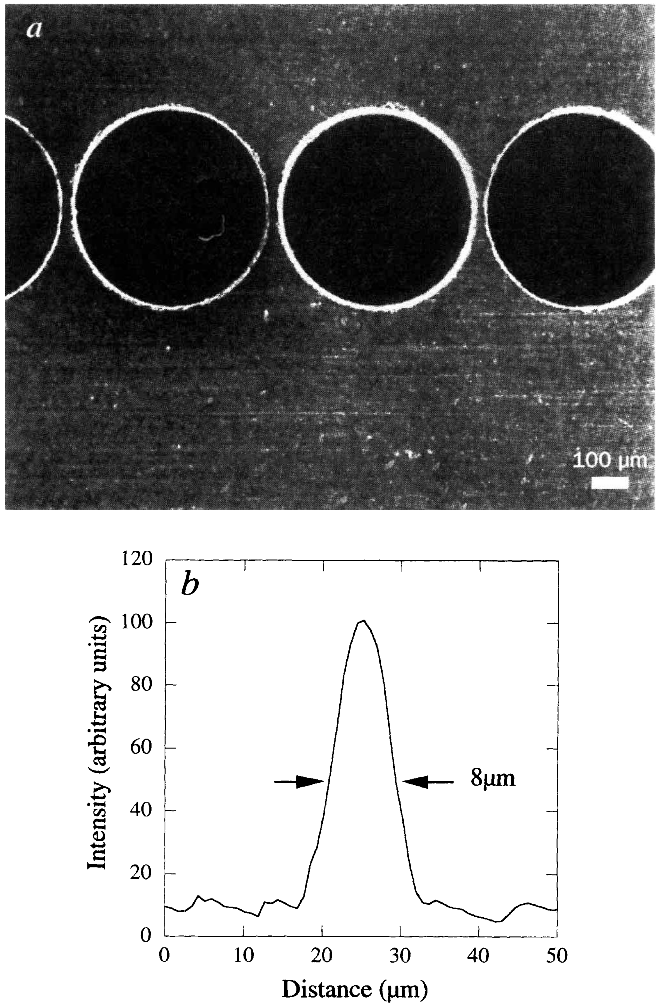

FIG. 3 a, Scanning electron microscope image of the tested compound refractive lens (CRL). 30 cylindrical holes of 300-μm radius were produced in an Al–Cu alloy (with 4 wt% Cu) plate using a computer-controlled drilling machine. Spacing d, the minimum alloy thickness between the holes, was ~25 μm. The length of the CRL was 19 mm. b, Measured profile of the focused X-ray beam taken at 1.8 m from the CRL. The width of the focal line is ~8 μm, which almost corresponds to the source size of 150 μm reduced by a demagnification factor $r_0/r_f = 20$.

TABLE 1 Calculated CRL parameters for boron and aluminium

Lens material	Energy (keV)	Number of holes	Effective aperture (μm)	Ideal gain	Real gain	CRL length (mm)
Boron	5	13	251	254	95	13
	10	55	211	359	93	55
	15	125	191	440	89	126
	20	222	177	508	84	224
	25	345	168	568	81	348
	30	501	160	622	78	506
	35	682	154	672	75	689
	40	892	149	719	73	901
Aluminium	5	11	85	22	0.2	11
	10	45	116	83	3	45
	20	184	163	336	18	186
	25	289	168	568	26	292
	30	417	160	622	31	421
	35	568	154	672	34	573
	40	743	149	718	37	750

Calculations were made under conditions typical for the ESRF beamlines: source size, 100 μm; source-to-lens distance, 50 m. Lens parameters were as follows: spacing between holes $d + 10\,\mu m$, hole radius $R = 500\,\mu m$, focal distance $F = 1$ m. The ideal gain (G) in the intensity at the focus for a point source was calculated according to ref. 4. The real gain (g) takes into account the finite source size and the attenuation of the X-rays owing to the absorption in the material between the holes[5]. The calculated focal spot size is $<1\,\mu m$ in all cases.

and the real gain versus the radius R of holes in a boron CRL. The number of holes N increases linearly with R and quadratically with energy. The gain is mainly controlled by absorption. Acceptable hole radii are in the range 250–600 μm. This matches well the beam size of third-generation synchrotron radiation sources like the European Synchrotron Radiation Facility (ESRF). Low-Z material with a high density is the best choice as CRL material because δ is proportional $Z\rho$ whereas absorption varies as $Z^4\rho$, where ρ is the material density. Our estimates show that boron is a very promising lens material for all energies considered. However, aluminium is easier to machine with modern computer-controlled drilling, so it can be used as a reasonable alternative. The number of holes is limited by the reasonable lengths of the array and the requirement to make the distance d (Fig. 1) as small as possible.

We manufactured a CRL in an aluminium alloy; a scanning electron microscope image of the compound lens is given in Fig. 3*a*. The lens was tested at the optics beamline (D-5) at the ESRF. The 14-keV radiation from the bending magnet (radiation source size 150 μm) was selected by a Si-111 monochromator. The width of the focal line measured by pinhole scan (Fig. 3*b*) was 8 μm, with a gain of 3 over a similar size produced with slits, in good agreement with theoretical estimations.

Comparing the CRL with bent-mirror optics, we note that the CRL does not change the beam path, whereas the mirror does. The compound lens is more compact that a mirror, as no bending mechanism is needed. Requirements for surface quality are significantly lower than for mirrors owing to a transmission geometry of scattering. CRL alignment is straightforward. It is also reasonable to compare the CRL with a Kumakhov lens. At first glance, both lens types seem to have a similar approach; mutliply a single element (a single capillary in a Kumakhov lens and a simple refractive lens in a CRL) to gain in optical performance. However, the Kumakhov lens is based on total reflection in a bundle of capillaries whereas the CRL is based on refraction. Unlike the case of the CRL, the Gauss lens formula cannot be applied to the polycapillary optics; the Kumakhov lens works as a collimator to collect centimetre-wide neutron and X-ray beams, but with a modest resolution (100 μm). The CRL, having a smaller collecting area (up to millimetre), is well adapted to the beam properties of third-generation synchrotron radiation sources and is capable of micrometre and submicrometre resolution. Therefore the two lens types should be considered as complementary with their own fields of application.

The CRL described above is a cylindrical lens focusing only in one direction. Focusing in both directions, resulting in a point focus, can be achieved in two ways. The simplest is to use two arrays of cylindrical holes in a crossed geometry; in fact the quality of the focal spot may be improved by using three arrays of holes at 120° to each other in a rod with hexagonal shape. The more complex approach to point focusing uses thin-walled hollow plastic spheres 0.5 mm in diameter. When the spheres are aligned in a tube with 0.5 mm inner diameter, and when the space between the spheres is filled with a liquid, genuine two-dimensional focusing may be achieved. For instance, a water lens with a row of 300 spheres of 0.5 mm diameter has a focal lengths of 1.8 m for 30-keV X-rays.

A CRL is easy and cheap to make. It is possible to make a composite lens consisting of a set of parallel rows of holes with different focal distances or different hole radii. To change the focal distance or working-energy range, one can easily switch from one array to another simply by moving the composite lens. Parabolic-shaped holes can be produced in a CRL by applying new technologies[6]. Such holes would allow the length of a CRL to be reduced by a factor of five, while keeping the same performance. By choice of a proper material and geometry, it may be possible to use a CRL in neutron applications. □

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